REMR TECHNICAL NOTE EM-CR-1.5

MECHANICAL PROPERTIES AND CORROSION BEHAVIOR OF STAINLESS STEELS FOR LOCK, DAM, AND HYDROELECTRIC PLANT APPLICATIONS

PURPOSE: To present typical mechanical property data, briefly discuss corrosion behavior and provide general guidelines regarding the viable and cost-effective use of stainless steels for lock, dam, and hydroelectric plant applications.

BACKGROUND: Carbon steels and low-alloy carbon steels have been the primary materials used for the construction of locks, dams, and hydroelectric plants. To a much lesser extent, components for these facilities have been traditionally fabricated from 400-series martensitic stainless steels (for example, Types 410 and 416) and 300-series austenitic stainless steels (for example, Types 302, 303, 304, 308, and 316). Although the traditionally used 300-series stainless steels normally have excellent corrosion resistance in most freshwater environments (Table 1), their yield strengths (about 35,000 psi in the normally used, annealed condition) are somewhat low for many applications. Further, bolts and nuts fabricated from the same 300-series material have exhibited serious threaded-area galling problems at a number of locks and dams. The 300-series stainless steels, including Type 316, which is formulated with a small molybdenum addition to resist pitting attack, also have a tendency to pit in waters containing more than about 1,000 ppm by weight chloride; they are also susceptible to oxygen-differential-type, concentration-cell corrosion under deposits and in crevices. Fortunately, for lock and dam applications, the austenitic grades of stainless steel do not experience chloride-induced, stress-corrosion cracking at temperatures less than about 150° F; they also exhibit excellent resistance to freshwater erosion corrosion.

The yield strength limitations of the 300-series stainless steels for Civil Works projects were originally overcome by using heat-treatable, 400-series stainless steels. Unfortunately, these alloys often do not exhibit the desired corrosion resistance. This lack of resistance is understandable because the metallurgy required to create a martensitic stainless steel necessitates that only limited amounts of chromium (generally, an upper limit of about 14 percent) be added to these alloys. The martensitic grades of stainless steel have a tendency to pit (Table 1), galvanically corrode, stress-corrosion crack, and suffer concentration-cell corrosion in many fresh waters. Cases are known in which heat-treated, 400-series stainless steels have failed from hydrogen-induced cracking because the components were only slightly overprotected by the cathodic protection systems designed to mitigate corrosion.

Traditionally used stainless steels have certain mechanical property and corrosion behavior limitations for lock, dam, and hydroelectric plant applications. Carefully selected and properly specified stainless steels, including the traditionally used materials, and especially some of the newer alloys,

Table 1

Corrosion Behavior of Carbon Steel and Stainless Steels

Based Upon 8 Years of Exposure to Mississippi River

Water at Winfield, MO (Ref a)

Material	General Corrosion Rate, mpy*	Pit Depth, mils	
		Max	Avg
Carbon steel	1.2	55	42
Type 410 stainless	**	27	16
Type 302 stainless	0	0	0

 * Mpy is mils (thousandths of an inch) per year.
** Weight loss was totally due to pitting attack.

however, can be viably and cost-effectively used for reducing maintenance costs and improving the availability of equipment and facilities without significant concern for the various forms of deterioration that have been associated with them (for example, crevice corrosion, intergranular attack, stress-corrosion cracking, hydrogen embrittlement, pitting, wear and galling, and galvanic corrosion).

DESCRIPTION: Fourteen stainless steels have been identified as being capable of reducing maintenance cost and increasing availability of lock, dam, and hydroelectric plant operations. These are (a) the wrought austenitic alloys NITRONIC 60 and Types 302, 303, 304, 308, and 316; (b) the wrought martensitic alloy Types 410, 416, and 431; (c) the wrought martensitic PH (precipitation-hardening) alloys 17-4PH and Custom 450; (d) the wrought semiaustenitic PH alloys 17-7PH; (e) the cast martensitic alloy CA-6NM; and (f) the cast austenitic-ferritic alloy CF-8.

The austenitic grades of stainless steel cannot be strengthened by heat treatment (Table 2). They can only be strengthened by cold working. Martensitic and the PH grades of stainless steel can be heat treated to microstructural conditions that provide a wide range of available mechanical properties.

Generally, the austenitic grades of stainless steel (for example, NITRONIC 60 and the 300-series) have better overall corrosion resistance than the other alloys identified in Table 2. Typical corrosion resistance, however, is heat-treatment dependent. For example, the corrosion resistance of 17-7PH stainless steel in both Conditions TH1050 and RH950 is superior to that of the heat-treatable, martensitic alloys; in Condition CH900, the general corrosion resistance of 17-7PH is comparable to that of Types 302 and 304 (Ref b). The corrosion resistance of Condition A 17-4PH stainless steel and the alloy when heat treated to its lower (albeit, still relatively high) strength levels is also comparable to Type 304 in most aqueous environments (Ref c). Similarly, the normal corrosion resistance of Custom 450 is superior to that of heat-treated Type 410 and similar to that of Type 304 (Ref d). NITRONIC 60 is unique in that it has better corrosion resistance to chloride-induced pitting attack than Type 316 (that is, an alloy specially formulated for resistance to

Table 2

Typical Mechanical Property Data for Stainless Steels Which
are Considered Applicable for Lock, Dam, and Hydroelectric
Plant Applications (Ref b-1)

Alloy	Form	Condition	UTS (ksi)	0.2 per-cent YS (ksi)	Percent E	Percent RA	Hard.	Impact Strength (ft-lb)
302	Bar	Annealed	85	35	60	70	Bhn 150	Izod 110
	Plate	Annealed	90	35	60	70	Rb 80	Izod 110
	Wire	Annealed	90	35	60	70	Rb 83	Izod 110
303	Bar	Annealed	90	35	50	55	Bhn 160	Izod 80
304	Bar	Annealed	85	35	60	71	Bhn 149	Izod 110
	Tube	Annealed	85	35	50	71	Rb 80	Izod 110
	Plate	Annealed	82	35	60	71	Bhn 145	Izod 110
308	Bar	Annealed	85	30	55	65	Rb 80	Izod 110
	Wire*	Annealed	95	60	50	-	-	Izod 110
316	Bar	Annealed	80	30	60	70	Rb 78	Izod 110
	Tube	Annealed	85	35	50	70	Rb 79	Izod 110
NITRONIC 60	Bar	Annealed	103	60	64	74	Rb 95	Charpy 240
		10% CD	120	91	51	68	Rc 24	-
		40% CD	195	153	20	57	Rc 38	-
410	Bar	Annealed	75	40	35	68	Rb 82	Izod 85
		OQ + 1 hr/300° F	195	150	15	55	Bhn 390	Izod 35
		OQ + 1 hr/1100° F	125	100	22	65	Bhn 262	Izod 35
	Plate	Annealed	70	35	30	68	Bhn 150	Izod 85
416	Bar	Annealed	75	40	30	60	Rb 82	Izod 20-64
		OQ + 1 hr/300° F	195	150	10	40	Rc 41	Izod 20
		OQ + 1 hr/1100° F	125	100	17	53	Rc 26	Izod 28
431	Bar	Annealed	125	95	20	55	Bhn 260	Izod 50
		OQ + 1 hr/500° F	198	149	16	55	Bhn 415	Izod 40
		OQ + 1 hr/1100° F	140	115	19	57	Bhn 302	Izod 48
17-4 PH	Bar	A	147	130	18	59	Rc 34	Charpy 47
		H900	200	185	14	50	Rc 44	Charpy 15
		H1025	170	165	15	56	Rc 38	Charpy 35
		H1075	165	150	16	58	Rc 36	Charpy 40
		H1100	150	135	17	58	Rc 35	Charpy 45
		H1150	145	125	19	60	Rc 33	Charpy 50
CUSTOM 450	Bar	SA	141	118	13	50	Rc 28	Charpy 95
		Aged at 850° F**	196	186	14	54	Rc 44	Charpy 20
		Aged at 900° F	195	186	14	55	Rc 42	Charpy 41
		Aged at 1000° F	173	169	17	63	Rc 39	Charpy 51
		Aged at 1150° F	142	91	23	69	Rc 28	Charpy 97
17-7 PH	Bar	RH950	185	150	6	10	Rc 41	-
		TH1050	170	140	6	25	Rc 38	-
CF-8	Cast	WQ from above 1400° F	77	37	55	-	Bhn 140	Charpy 74+
CA-6NM	Cast	AC from above 1750° F; tempered at 1100° F	120	100	24	60	Bhn 269	Charpy 70

Abbreviations: UTS = Ultimate Tensile Strength, YS = Yield Strength, E = Elongation, RA = Reduction in Area,
Bhn = Brinell Hardness Number, Rb = Rockwell B Hardness, Rc = Rockwell C Hardness, CD = Cold
Drawn, SA = Solution Annealed, WQ = Water Quenched, AC = Air Cooled, OQ = Oil Quenched. Those
conditions associated with 17-4 PH and 17-7 PH refer to special conditions developed by
Armco, Inc.

* Soft temper.

** Aging time of 4 hr for all temperatures.

+ Charpy keyhole notch; all other Charpy impact data are for V-notch.

chlorides) and unusually outstanding resistance to abrasion by suspended solids, galling, and cavitation when exposed to aqueous environments (Ref h).

GENERAL CORROSION BEHAVIOR, PITTING ATTACK, AND CONCENTRATION-CELL CORROSION:
The normally excellent corrosion resistance of stainless steels depends upon the formation and maintenance of an invisible, passive oxide film on their exposed surfaces. This film allows the stainless steels to exhibit potentials that are more noble (positive) than those they would have in the active (corroding) condition (that is, in the passive condition, the stainless steels have electrochemical characteristics similar to those of a noble metal such as gold). If this passive film is locally destroyed and cannot be readily repaired, pitting attack can be expected to occur in certain environments (especially, chloride-containing, aqueous environments). Similar localized corrosion in the form of oxygen-differential-type, concentration-cell corrosion can occur in crevices and under deposits (that is, occluded cells) where there is insufficient oxygen for maintaining the passive film. The absence of oxygen in the occluded cells causes the stainless steel to become electrochemically active (that is, become anodic and exhibit a relatively negative potential) relative to that in which the passive film is still intact. This form of corrosion can be especially deleterious because it is usually facilitated by a large driving voltage between the passive and active regions and an undesirably large cathode-to-anode area ratio.

Significant insight regarding corrosion behavior can be obtained from the analysis of data obtained from laboratory-conducted, anodic polarization tests. In general, stainless steels having very negative primary passivation potentials (E) and small critical current densities for passivation (i_c) normally passivate quite readily in aerated aqueous environments. Once passivated, the alloys will normally corrode at very low rates in accordance with Faraday's Law and their passive current densities (i_p). If the oxidizing characteristics of the environment are overly powerful, alloys can be spontaneously polarized to potentials sufficiently noble (positive) that they will be subjected to accelerated corrosion and pitting attack in the transpassive potential region (that is, corrode at the high current densities associated with the potentials more noble than E_{tp}). From this brief discussion, the desirable anodic polarization characteristics for stainless steels would be (a) low values of i_c, (b) very negative values for E_p, (c) low values of i_p, (d) highly positive values for E_{tp}, and (e) large potential differences between E_p and E_{tp}.

Values of E_p, i_c, i_p, and E_{tp} for selected stainless steels in deaerated, 1N sulfuric acid are included in Table 3. As would be expected, the addition of chlorides reduces the passive potential regions (that is, the values of $E_{tp} - E_p$) and increased the magnitudes of i_c and i_p (Ref i). Similar adverse phenomena occur, in general, when the temperature of the environment is increased or its pH is lowered. The deleterious, field-observed effects of high-operating temperatures, acidic environments, and the presence of chlorides on stainless steels have been verified and explained by the results of laboratory testing. Additional laboratory testing has also showed that, as might be expected, all of the stainless steels included in

Table 3 spontaneously passivate in aerated Columbia River water and corrode in the passive potential region at very low uniform corrosion rates (that is, corrosion rates associated with i_p values of 2.8 to 8.2 × 10^{-7} amp/cm^2) (Ref 1).

Table 3

Anodic Polarization Characteristics for Selected Stainless Steels in Deaerated 1N Sulfuric Acid at Ambient Temperature (Ref 1)

Stainless Steel/Condition*	E_p, Volt vs. SCE**	i_c, amp/cm^2	i_p, amp/cm^2	E_{tp}, Volt vs. SCE
Type 304, Annealed + 10% CW	-0.347	4.28 × 10^{-4}	3.27 × 10^{-6}	+0.89
Type 410/Annealed	-0.376	1.49 × 10^{-2}	5.27 × 10^{-6}	+0.81
Custom 450/SA	-0.256	3.68 × 10^{-5}	1.92 × 10^{-6}	+0.92
Custom 450/Aged at 1150° F	-0.277	2.63 × 10^{-5}	2.00 × 10^{-6}	+0.87
17-4PH/Condition A	-0.269	1.60 × 10^{-4}	2.02 × 10^{-6}	+0.89
17-4PH/H1150	-0.312	8.75 × 10^{-5}	2.53 × 10^{-6}	+0.88
NITRONIC 60/Annealed	-0.346	3.63 × 10^{-4}	1.58 × 10^{-6}	+0.92

* See Table 2 for condition abbreviations.
** SCE refers to the saturated calomel electrode.

GALVANIC CORROSION: The initial driving voltage for dissimilar-metal/ alloy/material corrosion can be estimated when a galvanic series exists for the environment of concern. In general, the larger the driving voltage, the higher will be the initial rate of attack to the less noble alloy when dissimilar metals/alloys are metallically connected and exposed to a corrosive environment. For example, using the galvanic series for the alloys included in Table 4 (Ref 1), one can see that NITRONIC 60 has a potential of -0.327 v referenced to a saturated calomel electrode (SCE), whereas American Society for Testing and Materials (ASTM) A 36 steel has a potential of -0.574 v in aerated, ambient-temperature, 0.5M sodium chloride solution. If the two alloys were metallically connected and exposed to this environment, NITRONIC 60 (that is, the alloy with the more positive potential) would be cathodic to the ASTM A 36 steel (that is, ASTM A 36 steel would be the anode in the corrosion cell). The ASTM A 36 steel would experience accelerated galvanic corrosion at an initial driving voltage of 0.247 v (that is, the potential difference between the two materials); the NITRONIC 60 would, at least in part, be cathodically protected.

Examination of the data in Table 4 provides insight regarding the mitigation of galvanic corrosion. Materials should be selected so that those which will be metallically connected will have potentials close to each other in the environment where they will be exposed. Alternatively, the materials can sometimes be electrically isolated from each other. Galvanic corrosion

problems can also be reduced by ensuring that the cathodic area is small compared with that of the anodic area. Large cathode-to-anode area ratios must be avoided if unacceptable galvanic corrosion is to be effectively avoided. Coatings in conjunction with cathodic protection have also been effectively used to mitigate galvanic corrosion.

Table 4

Galvanic Series for Selected Alloys in Ambient-

Temperature, 0.5M Sodium Chloride Solution (Ref i)

Alloy/Condition*	Potential, Volt, vs. SCE	Initial Driving Voltage of Alloy Coupled to ASTM A 36 Steel, Volt
NITRONIC 60/Annealed	-0.327	0.247
Type 304/Annealed + 10% CW	-0.328	0.246
Custom 450/SA	-0.330	0.244
Custom 450/Aged at 1150° F	-0.362	0.212
17-4PH/H1150	-0.384	0.190
17-4PH/Condition A	-0.396	0.178
Type 410/Annealed	-0.488	0.086
ASTM A 36/Normalized	-0.574	0.000

* See Table 3 for condition abbreviations.

It must be understood that the initial driving voltage for galvanic corrosion will normally decrease with time because of polarization at the anodes and cathodes. This decrease in the driving voltage, in turn, reduces the galvanic corrosion current density at the anodes and lowers their corrosion rates. For equal anodic and cathodic areas, the galvanic corrosion current densities obtained for ASTM A 36 steel when connected to selected grades of stainless steel and exposed to aerated, ambient-temperature, 0.5M sodium chloride solution for an extended time period are presented in Table 5 (Ref i). Based upon these data, galvanic corrosion of ASTM A 36 steel is not significantly affected by the chemistry or metallurgical condition of the stainless steel involved; the corrosion current densities for the ASTM A 36 steel vary between 1.4 and 2.5×10^{-5} amp/cm^2.

CAVITATION: Tests conducted in accordance with ASTM G 32 have allowed a ranking to be made for stainless steels and a low-alloy carbon steel with regards to their cavitation resistance (Table 6) (Ref i). Not unexpectedly, NITRONIC 60 has the best cavitation resistance of the materials evaluated. Similar cavitation resistance results have been obtained for stainless steels exposed to jet-impingement by river water; the relative cavitation depth damages for NITRONIC 60, 17-4PH, Type 316, and CA-6NM were reported as being 1.0,

Table 5

Galvanic Corrosion Current Densities for ASTM A 36 Steel

When Metallically Connected to an Equal Area of Stain-

less Steel and Exposed to Aerated, Ambient-Temperature,

0.5M Sodium Chloride Solution (Ref 1)

Stainless Steel/Condition*	Galvanic Corrosion Current Density for A 36 Steel, amp/cm^2
NITRONIC 60/Annealed	1.4×10^{-5}
Type 304/Annealed + 10% CW	2.1×10^{-5}
Custom 450/SA	2.0×10^{-5}
Custom 450/Aged at 1150° F	1.6×10^{-5}
17-4PH/H1150	1.9×10^{-5}
17-4PH/Condition A	2.2×10^{-5}
Type 410/Annealed	2.5×10^{-5}

* See Table 2 for condition abbreviations.

Table 6

Ranking of Stainless Steels Compared with a Low-Alloy

Carbon-Steel with Regards to Cavitation Resistance

According to the Results of ASTM G 32

Testing (Ref 1)

Ranking	Stainless Steel/Condition*	Brinell Hardness No.	Erosion Rate, in./year
1	NITRONIC 60/Annealed	201	0.4
2	17-4PH/H1150	388	1.2
3	Custom 450/Aged at 1150° F	320	1.3
4	17-4PH/Condition A	321	1.6
5	Type 304/Annealed + 10% CW	197	1.7
6	Custom 450/SA	270	1.9
7	AISI 4130 Steel/Normalized	286	2.5
8	Type 410/Annealed	223	3.8

* See Table 2 for condition abbreviations.

1.9, 3.7, and 6.6 (Ref j). These data clearly indicate that cast NITRONIC 60 could be a viable alternative for CA-6NM where cavitation is a concern.

GALLING: The "button and block" galling test has been used to evaluate the adhesive wear resistance of various stainless steels under nonlubricated conditions (Ref k). Specimens were considered to be galled if deep scoring and heavy surface damage were evident during examination of the surfaces at 10X magnification. The lightest load that caused galling was used to calculate the "threshold galling stress." Threshold galling stresses for selected stainless steel combinations are included in Table 7 (Ref k).

Examination of the data in Table 7 establishes that many contacting stainless steel combinations are highly susceptible to galling. Most important, the data show that NITRONIC 60 can be used in contact with many stainless steels without concern for galling. Galling problems associated with the use of Type 304 nuts and bolts could very well be eliminated by fabricating one of the components from NITRONIC 60.

Table 7

Threshold Galling Stresses (psi) for Stainless Steels

According to the Results of "Button and Block"

Galling Tests (Ref k)

Block Material	Button Material and Threshold Galling Stress, psi						
	Type 410	Type 416	Type 303	Type 304	Type 316	17-4PH	NITRONIC 60
Type 410*	3	4	4	2	2	3	50+§§
Type 416**	4	13	9	24	42	2	50+
Type 303+	4	9	2	2	3	3	50+
Type 304++	2	24	2	2	2	2	50+
Type 316†	2	42	3	2	2	2	38
17-4PH††	3	2	2	2	2	2	50+
NITRONIC 60§	50+	50+	50+	50+	38	50+	50

 * Hardened and stress relieved to Bhn 352.
** Hardened and stress relieved to Bhn 342.
 + Annealed to Bhn 153.
++ Annealed to Bhn 140.
 † Annealed to Bhn 150.
†† Condition RH950 to Bhn 415.
 § Annealed to Bhn 205.
§§ 50+ indicates that no galling occurred at 50,000 psi.

CONCLUSIONS: Stainless steels are viable and cost-effective options for many lock, dam, and hydroelectric plant applications. Alloys, however, must be carefully selected; the components must be properly designed and fabricated. No single stainless steel is available that exhibits the desired mechanical

properties and corrosion resistance for all applications. Considering the wide variety of stainless steels presently available, their advantageous use for Civil Works projects is probably limited only by the imaginations of the design and maintenance engineers.

REFERENCES:

a. Komp, M. E., and Schmidt, R. J. 1966. "Selection and Application of Stainless Steels for Corrosive Environments," in Methods of Materials Selection, ed. by E. D. Verink, Jr., University Symposium on Methods of Material Selection, Gainesville, FL.

b. Armco, Inc. 1984. Armco Precipitation-Hardening Stainless Steels, Middletown, OH.

c. _____. 1983. Armco 17-4 PH Precipitation-Hardening Stainless Steel Wire and Bar, Middletown, OH.

d. Carpenter Technology Corporation. 1971. Carpenter Custom 450, Reading, PA.

e. Peckner, D., and Bernstein, I. M. 1977. Handbook of Stainless Steels, McGraw-Hill, New York.

f. American Society for Metals. 1976. Source Book on Stainless Steels, Metals Park, OH.

g. Carpenter Technology Corporation. 1965. Working Data: Carpenter Stainless and Heat-Resisting Steels, Reading, PA.

h. Armco, Inc. 1984. Armco NITRONIC 60 Stainless Steel, Middletown, OH.

i. Segan, E. G., and others. 1982. "Wrought Stainless Steel Fasteners for Civil Works Applications," Technical Report M-306, US Army Construction Engineering Research Laboratory, Champaign, IL.

j. Schumacher, W. J. 1977. "A New Stainless Alloy for the Hydro-electric Industry," in American Society of Mechanical Engineers, Fluids Engineering Division, American Society of Mechanical Engineers, New York, pp 167-169.

k. _____. 1977. "Wear and Galling Can Knock Out Equipment," Chemical Engineering, Vol 84, No. 10, pp 155-160.